Autonomous Vision Guided Safe and Precise Landing

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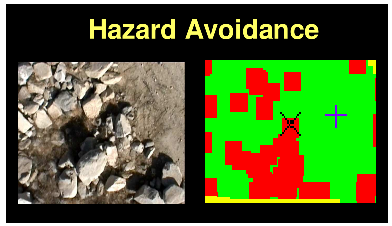

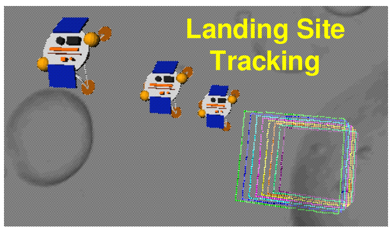

TASK OBJECTIVE

To develop and test algorithms for autonomous vision-based safe and precise landing on hazardous terrain

MAJOR PRODUCTS

Algorithms for real-time decision making during landing based on surface reconstruction from passive imaging. Demonstration of algorithms in a realistic environment using an aerial testbed.

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TEAM: JPL, USC, Caltech

YEAR	DELIVERABLE
FY01	Onboard 3-D Surface Reconstruction
FY02	Hazard Detection and Avoidance
FY03	Target Tracking for Precision Landing

NASA RELEVANCE

Enables missions that require a safe and precise landing capability, such as Mars Landers/Scouts, Comet Nucleus Sample Return, Europa Lander, Titan Organics Explorer

ACCOMPLISHMENTS TO DATE

- FY01 & FY02 algorithms coded and tested off-line. Plan to demonstrate vision-based safe site selection with autonomous helicopter testbed by the end of FY02.
- Infused subset of our technology into Mars '03 mission
- Demonstrated autonomous flight with helicopter testbed
- Presented two papers at 2002 International Conference on Robotics and Automation

Research Challenges

- Safe and precise landing in unstructured, unknown hazardous terrain in real-time with limited computational resources

State of the Art (JPL)

- Hazard Tolerance
  - SOA: landing in lightly crated terrain with 100 meter diameter craters and 1 meter high rocks for Mars Exploration Rover '03 mission
  - Improvement: landing in moderately to heavily crated terrain with 200 to 400 meter diameter craters and 2 to 4 meter high rocks using vision-based hazard detection and safe landing
- Precision Landing
  - SOA: ability to sense and track surface features for precision landing does not currently exist
  - Improvement: land within a 1 meter error ellipse beginning from 100 meter altitude using vision-based landmark tracking

State of the Art (Other research centers)

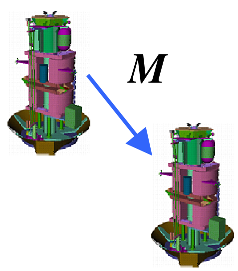
- Academia
  - University of Southern California and Berkeley have achieved autonomous vision-based landing using known landmarks. Both were in relatively benign terrain. Others (Carnegie Mellon, e.g.) have used vision for navigation but not landing.
- Military
  - DARPA and ONR have an interest in autonomous vision-based landing, but to my knowledge have not achieved this goal. The JPL Machine Vision Group is working with the DARPA Organic Air Vehicles program to help develop a vision based "perch and stare" landing capability

Autonomous Vision Guided Safe and Precise Landing: Technologies

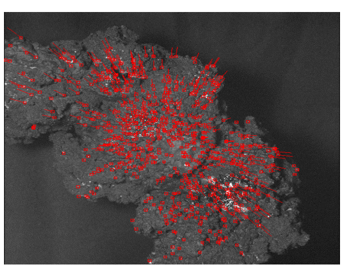
Intelligent Systems Program

FY01

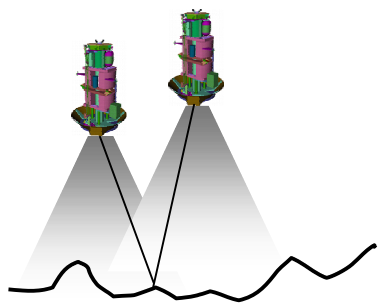
Multi-Sensor State Estimation



Altimetry, imagery and inertial measurements contribute to state estimation.



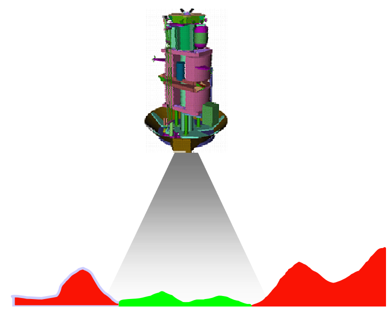
Efficient 3-D Structure Recovery



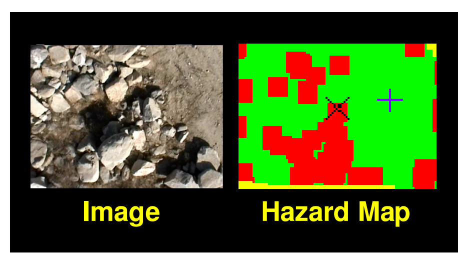
Surface reconstructed from pair of images acquired from single camera.

FY02

Hazard Detection and Avoidance

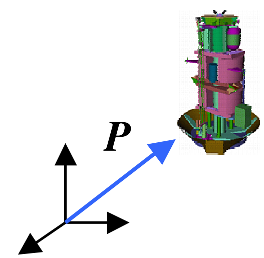


Hazards detected in terrain map generated from passive imagery (safe zones are in green.)

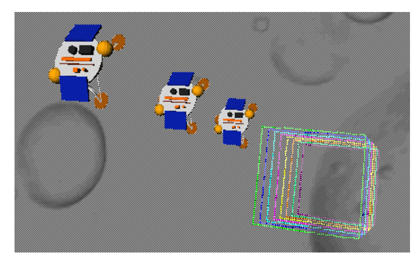


FY03

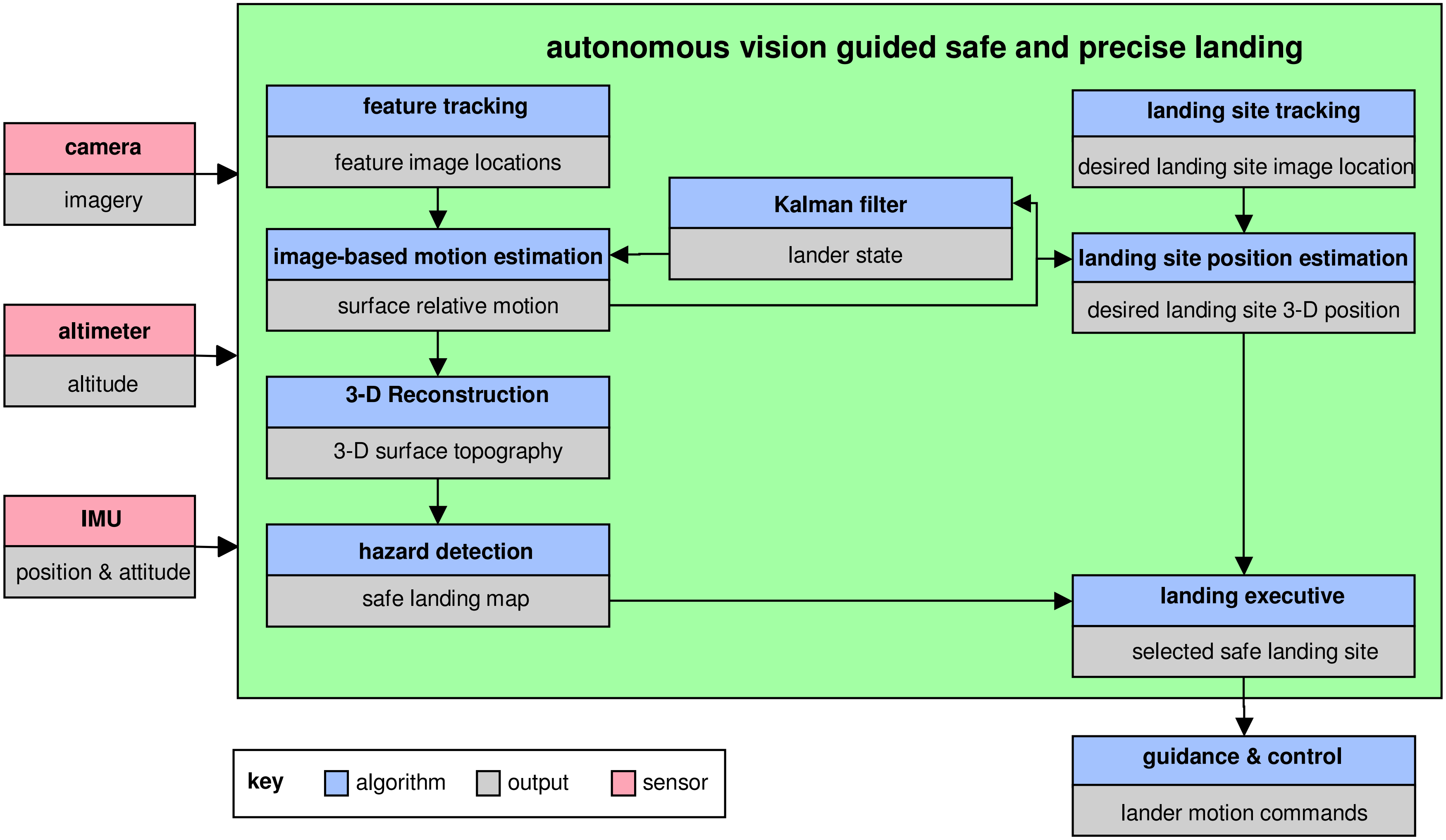
Precision Landing Through Surface Tracking



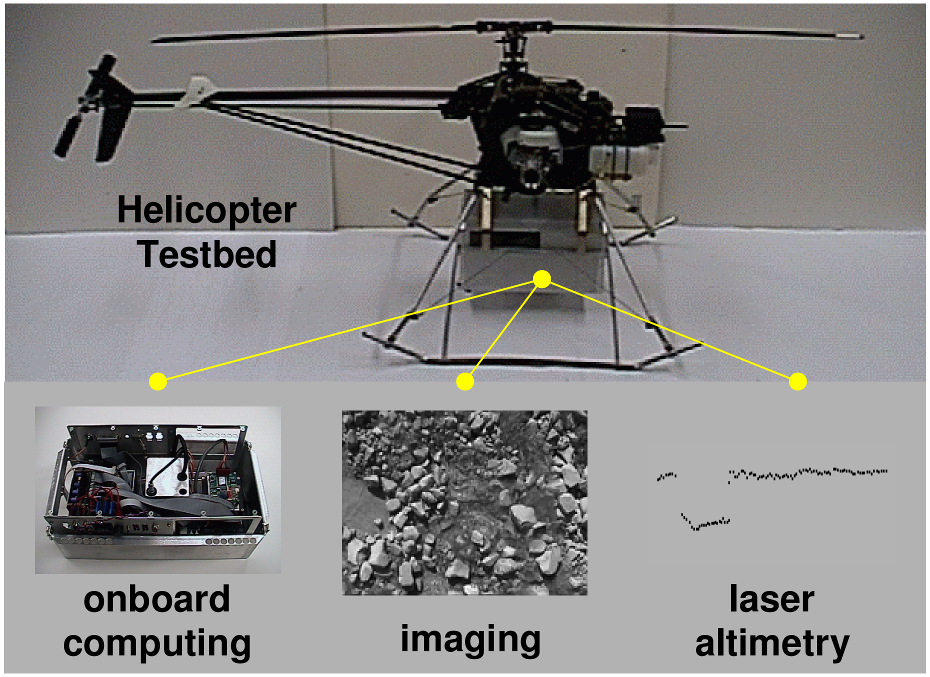
Landing site modeled as a 3-D faceted surface to allow for 6 DoF tracking.



Safe and Precise Landing Block Diagram



Autonomous Helicopter Testbed



Commercial Model Helicopter

- 9 kg payload capacity
- 1.8 meter main rotor diameter
- Twin cylinder engine, runs on gas/oil mixture
- 15-20 minute flight on single tank of fuel
- Controlled using standard RC modeler (72 MHz)

Sensors

- CCD imager (640x480 grayscale)
- Laser altimeter
- IMU
- DGPS (2 cm CEP accuracy)
- Compass

Onboard Computing

- PC/104 architecture
- 700 MHz PIII CPU with 128Mb DRAM and 128 Mb flash disk
- Framegrabber
- Timer/counter and DIO
- Quad serial card

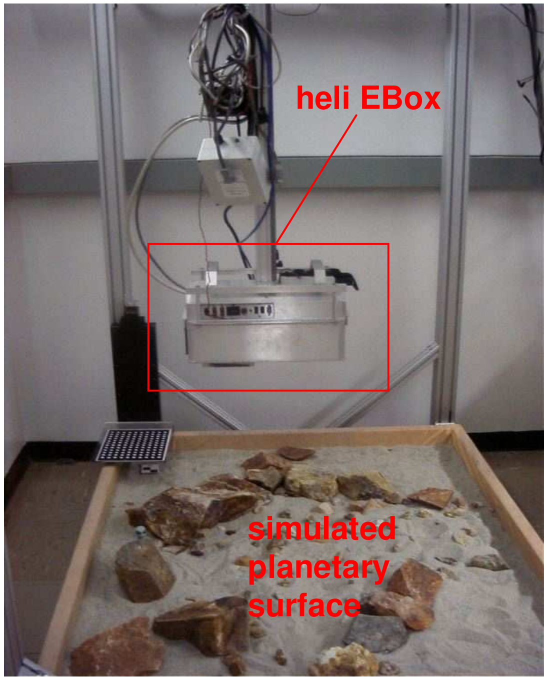
Communication and Control

- 11 Mbit/s wireless ethernet link
- Laptop for robot control and telemetry display

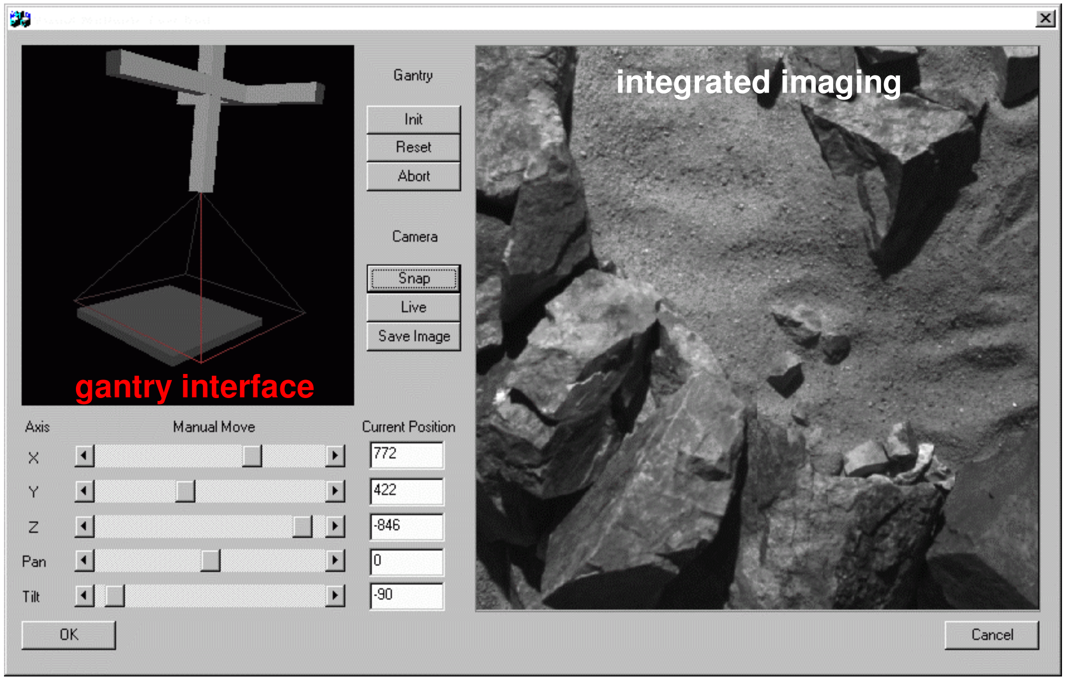
Gantry Testbed

- Hardware in the loop testbed for collecting data of simulated planetary surface for algorithm development and testing.
- 5 DoF gantry provides position and attitude control with ground truth measurements
- Computing and sensor electronics from Helicopter Testbed mounted in gantry
- User interface allows interactive control of gantry position and attitude

5 DoF Gantry



User Interface



Task Accomplishments

Multi-Sensor State Estimation

- design, code and test of indirect KF state estimator completed
- validation on helicopter testbed in progress

3-D Structure Recovery & Hazard Detection

- robust and efficient two frame motion estimation, 3-D structure recovery and hazard detection algorithms designed, coded and tested
- validation on helicopter testbed in progress

Gantry Testbed

- gantry used to validate KF, motion estimation and 3-D structure recovery algorithms

Helicopter Testbed

- autonomous control demonstrated on June 8, 2002

Technology Infusion

- subset of our technology (DIMES: Descent Image Motion Estimation Subsystem) infused into Mars Exploration Rover mission

Results Dissemination

- two papers co-authored (one with CalTech subcontractor and one with USC subcontractor) and presented at the 2002 International Conference on Robotics and Automation

Multi-Sensor State Estimation Results

- Multi-sensor state estimation provides improved state estimation over vision or IMU alone
- Gantry is ground truth in the plot below
- Average absolute errors in p = [x y z] between the gantry (truth) and …
  - … IMU alone was [53.5 464.7 126.1] mm (not shown on plot below due to magnitude of errors)
  - … imagery alone was [17.4 41.4 29.9] mm
  - … IMU and imagery combined was [4.5 4.7 4.2] mm.
- More accurate state estimation improves performance of our safe and precise landing algorithms

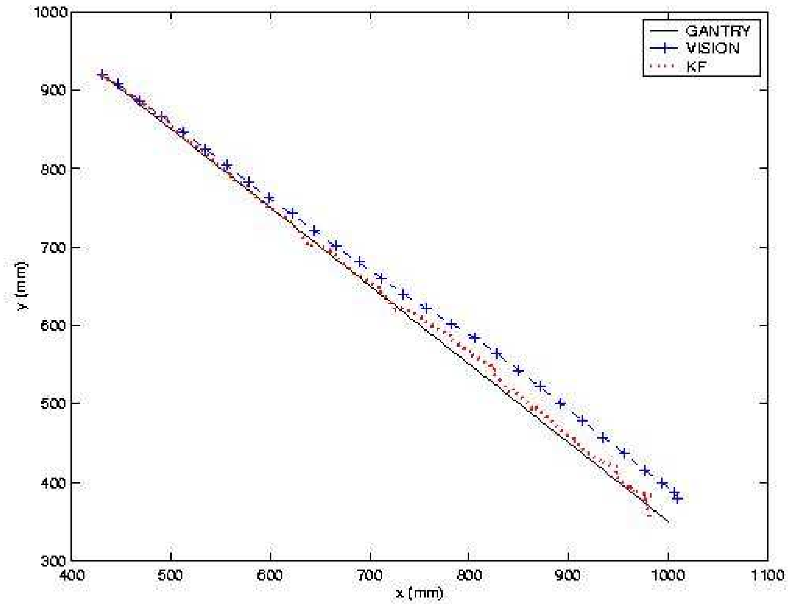


Image-Based Motion Estimation

- Image-based motion estimation (IBME) computes change in position and attitude between images by tracking multiple features in the images
- Features are pixel locations and the surrounding image intensity neighborhood (feature window)
- Feature tracks are computed by minimizing a cost function, defined by image intensity difference between feature windows, over the 2-D space of possible image displacements
- *Problem*: IBME alone cannot solve for scale or disambiguate between small rotations or translations
- *Solution*: combine image-based motion estimates with additional sensors; laser altimetry to solve for scale and IMU data to resolve rotation/translation ambiguities

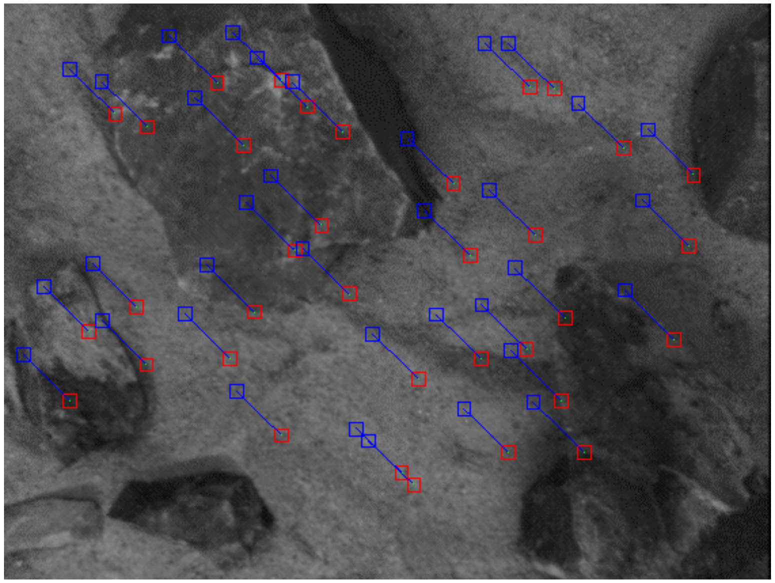
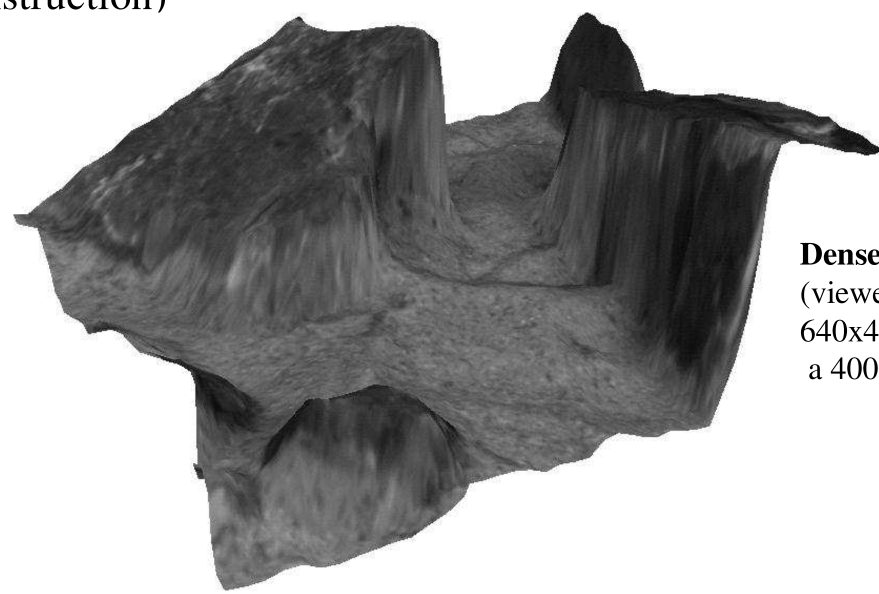


Image-based motion estimation
640x480 image required 1.16sec on a 400 MHz R12000 RISC processor

Efficient 3-D Structure Recovery

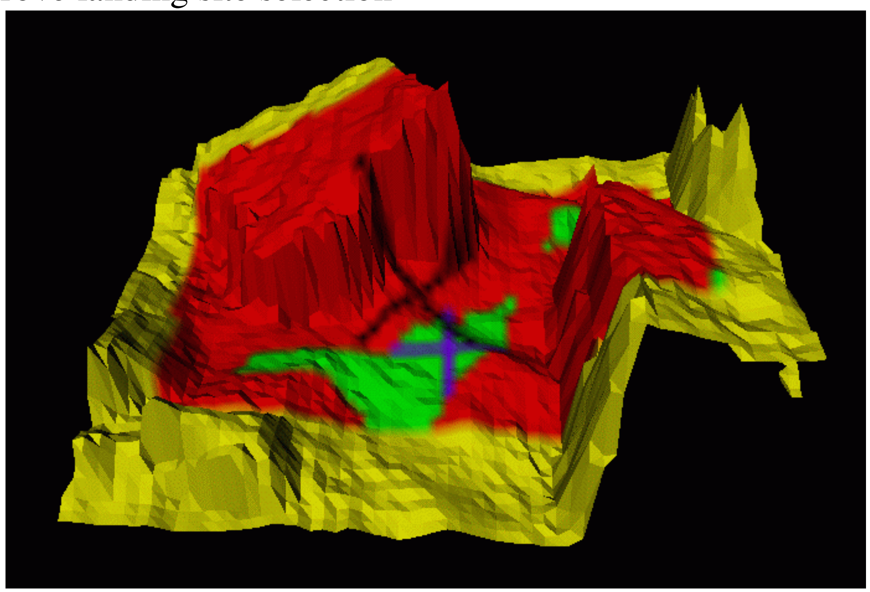
- Use computed motion estimate between images and a camera model to determine the 3-D position of features through triangulation
- *Structure from Motion:* computation of structure for a small number of features is tightly integrated with the estimation of motion
- *Motion Stereo:* dense topographic map generated after motion estimation
- *Problem*: Image rectification breaks down under general motion (e.g., 6 DoF motion) and algorithms to produce high-resolution reconstructions are memory and CPU intensive
- *Solution*: Combine positive attributes from structure from motion (general motion) and motion stereo (dense reconstruction)



Dense 3-D structure recovery
(viewed from lower-left of 2-D image)
640x480 image required 2.03 sec on a 400 MHz R12000 RISC processor

Hazard Detection/Safe Site Selection

- Compute slope and roughness at each location in a terrain map
- When slope or roughness exceeds a threshold, this location is called a hazard
- Hazards are grown by size of the lander and location furthest from hazards is chosen as landing site
- Problems:
  - Decisions are made based upon current view only
  - Decisions are made based upon slope and roughness constraints only
- Solutions:
  - *Temporal accumulation of data:* combine measurements from multiple views
  - *Generality:* combine slope and roughness constraints with other constraints such as remaining fuel or scientific value of a site to improve landing site selection



Hazard Detection/Safe Site Selection (Red: unsafe, Green: safe, Yellow: unknown, Blue X: current landing site, Black X: old landing site)

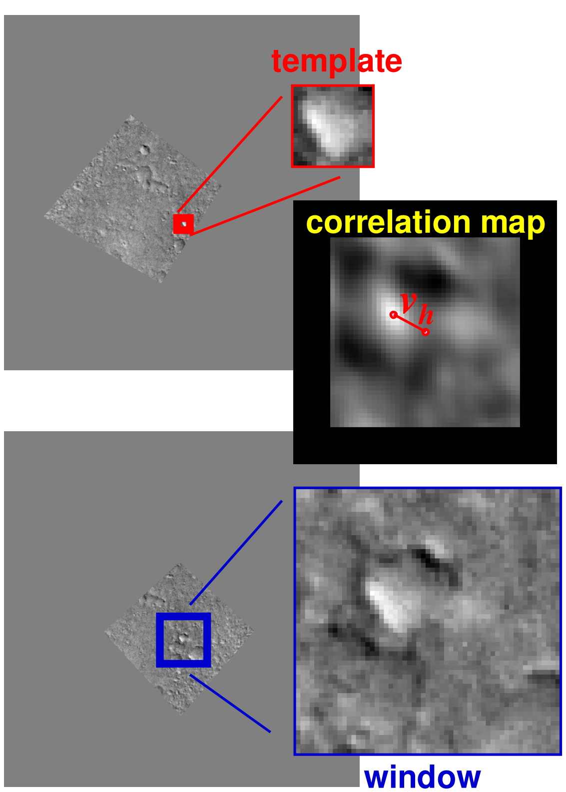
640x480 image required 0.14 sec on a 400 MHz R12000 RISC processor

Autonomous Helicopter Flight (08-Jun-02)

movieJPLHeliTestbed_08Jun02.mov

Technology Infusion into Mars Exploration Rover

APPROACH



Input
- 3 1024x256 images
- 3 altitudes
- 3 attitudes

Output
- average horizontal velocity

Current Status
- FSW development and Field testing for MER Project

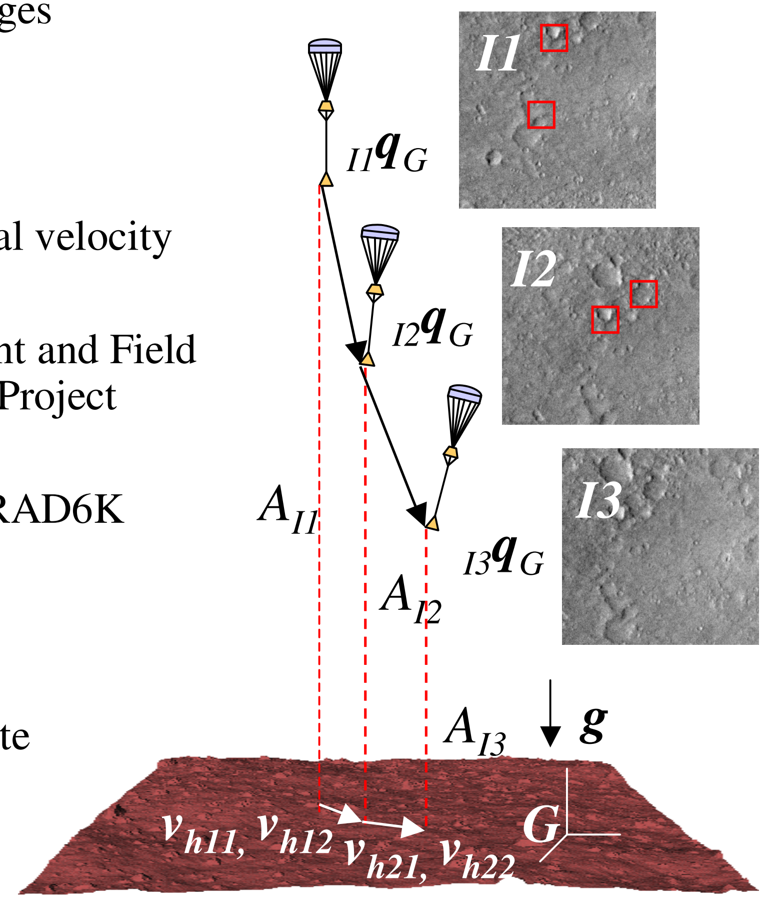
Timing
- 1.5s on 20MHz RAD6K

Operating Altitude
- 1600-1200m

Update rate
- 1 velocity estimate

Accuracy
- 5 m/s at 1400 m

SCENARIO



Descent Image Motion Estimation Subsystem (DIMES)

Developers: Andrew Johnson and Yang Cheng

Upcoming Task Milestones

September '02

Demonstrate closed-loop control of autonomous helicopter testbed using safe landing algorithms to locate and hover over safe site

December '02

Demonstrate closed-loop control of autonomous helicopter testbed using safe landing algorithms to locate and land in safe site

March '03

Demonstrate automated precision landing algorithms off-line using previously gathered helicopter testbed imagery

June '03

Demonstrate closed-loop control of autonomous helicopter testbed using surface tracking algorithms for precise hovering over safe site

September '03

Demonstrate closed-loop control of autonomous helicopter testbed using surface tracking algorithms for precise landing in safe site